



Invited Plenary Talk
Spring Conference of the Korean Space Science Society (KSSS)
Gangneung-si, Gangwon-do, Republic of Korea

SPACE RADIATION RESEARCH AT NASA

John Norbury

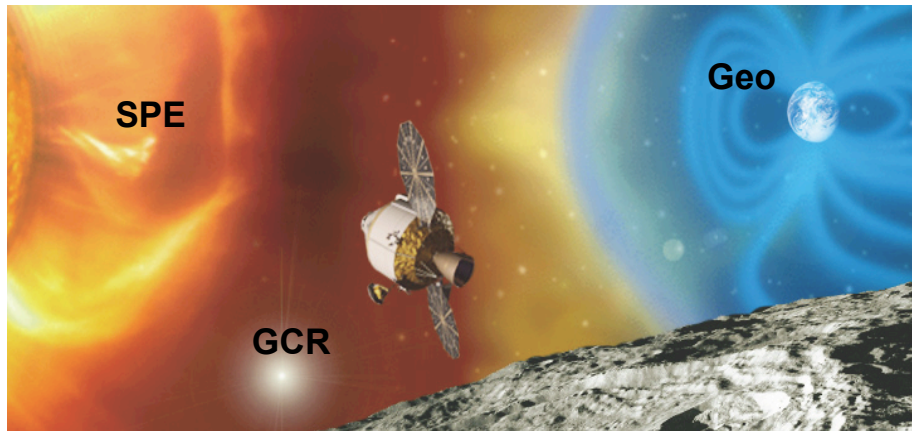
NASA Langley Research Center, Hampton, Virginia, USA

Friday April 29, 2016

OUTLINE

- 1 3 SOURCES OF SPACE RADIATION
- 2 RADIATION & DOSE
- 3 NUCLEAR & PARTICLE PHYSICS & TRANSPORT
- 4 MOON, MARS, JUPITER, SATURN
- 5 CONCLUSIONS

3 SOURCES OF SPACE RADIATION



<https://oltaris.larc.nasa.gov>

SPE = Solar Particle Event GCR = Galactic Cosmic Rays

Geo = Geomagnetically trapped particles

GCR COMPOSITION, SPECTRUM, ORIGIN

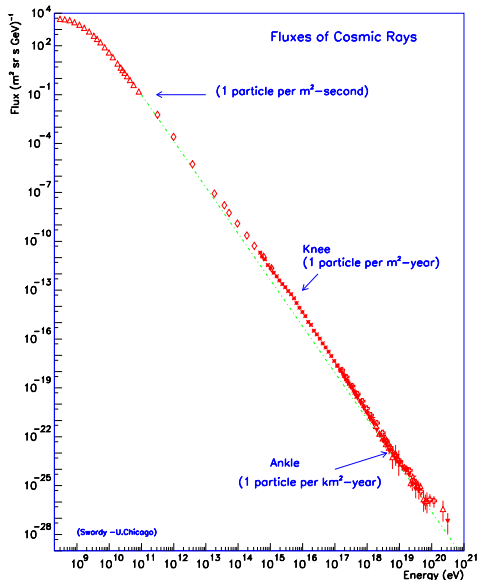
3 regions

- High Energy < PeV
- Very High Energy (knee) PeV - EeV
- Ultra High Energy (ankle) > EeV

keV = 10^3 eV MeV = 10^6 eV
GeV = 10^9 eV TeV = 10^{12} eV
PeV = 10^{15} eV EeV = 10^{18} eV
ZeV = 10^{21} eV

Large Hadron Collider

14 TeV cm \Rightarrow 400 PeV lab



Volk, ICRC, 2001:3

GCR HIGH ENERGY < PEV

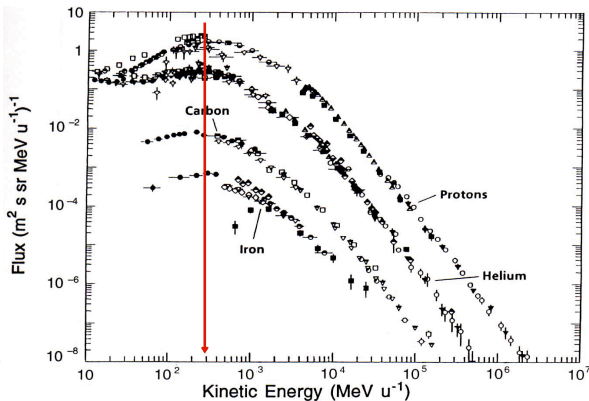
Space radiation problem

GCR (primary) composition

- 98% nuclei, 2% $e^+ e^-$
- Nuclear component:
 - 87% Hydrogen
 - 12% Helium
 - 1% heavy nuclei

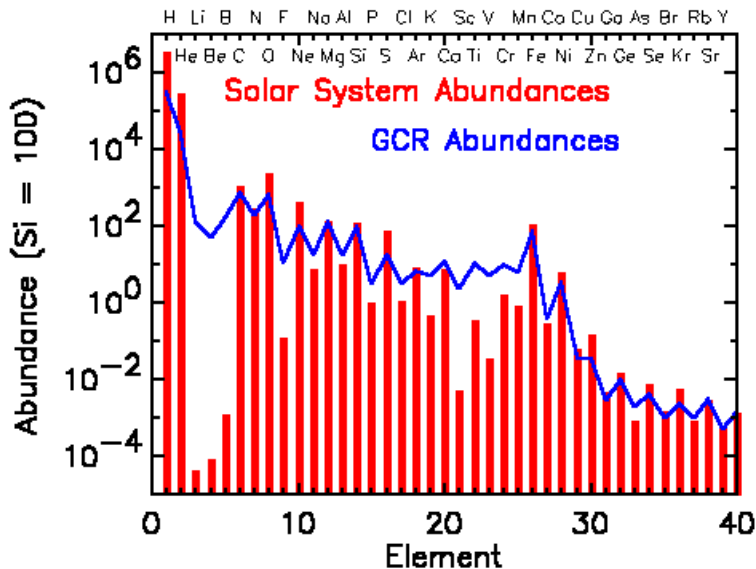
GCR origin

- Emitted in stellar wind & flares & accelerated by supernova shock waves (within our Galaxy)



Simpson, Ann. Rev. Nucl. Part. Sci. vol.33, p.323, 1983

GCR HIGH ENERGY < PEV



<http://imagine.gsfc.nasa.gov/Images/science/abund2.gif>

APPLIED NUCLEAR PHYSICS RESEARCH



Relative contribution in **fluence**, **dose** and **dose equivalent** of different elements in the GCR spectrum. Calculation is an average over 1 year in solar minimum behind 5 g/cm² Al shielding.

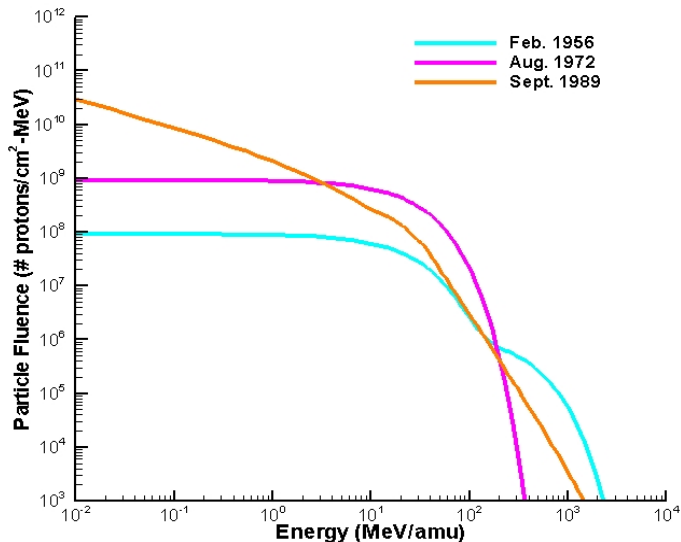
Durante & Cucinotta, Nat. Rev. Canc. vol.8, p.465, 2008

SOLAR PARTICLES

e, p & some heavy nuclei

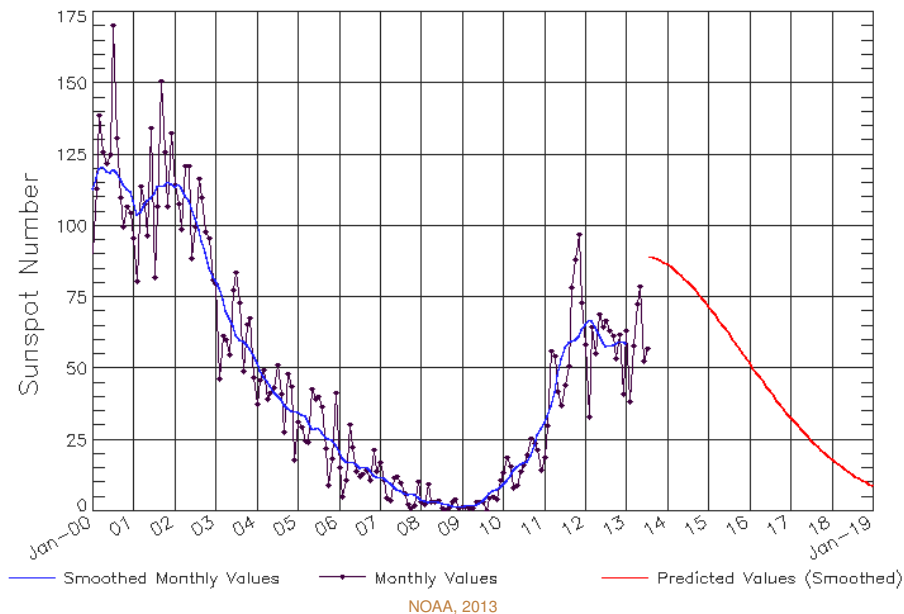
$< 1 \text{ GeV/N}$

($v \sim 0.9c$)



SPE Proton spectra

Cloudsley et al., AIAA, 2006



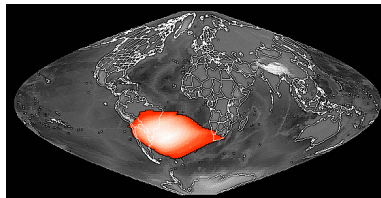
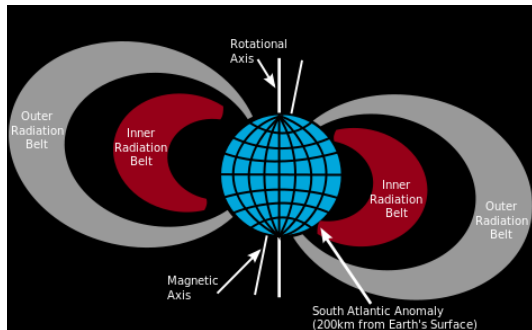
GEOMAGNETICALLY TRAPPED PARTICLES

Inner belt: 0 - 3 R_E = 18,000 km - mainly p

- Starts about 3,000 km
- But SAA dips down to 400 km

Outer belt: 3 - 12 R_E = 36,000 km (e,p) - mainly e

(LEO: 200 - 500 km GEO: 22,000 miles = 35,000 km)



Wikipedia, 2014

<http://science1.nasa.gov/science-news/science-at-nasa/2001>

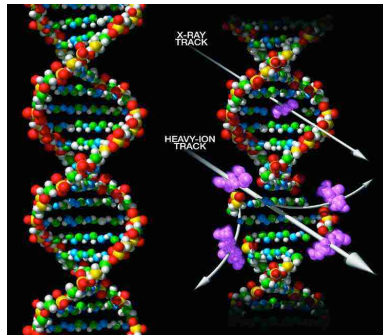
RADIATION & DOSE

Unit of absorbed dose:

1 Gray == 1 J/kg

Radiation quality factor Q

Sievert = Gray $\times Q$



<http://www.nasa.gov/centers/marshall/multimedia/photos/2003/photos03-183.html>

ICRP estimate: 5% per Gy

1 in 20,000 risk of fatal cancer per 1 mSv dose (lifetime)

RADIATION & DOSE

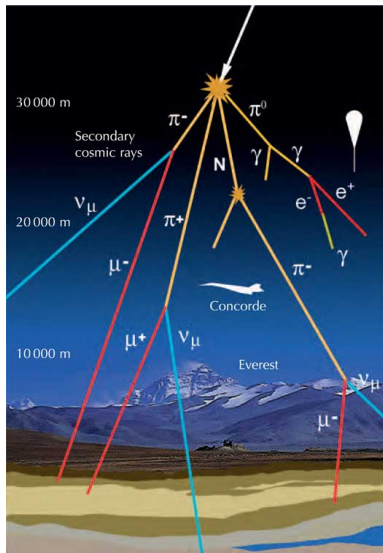
	Dose Equiv. (mSv)
Chest x-ray	0.1
USA annual background	4
Public annual limit (above background)	1
International Airline crews	4
Radiation worker annual limit	50
No observed effects (Abomb, instant)	200
Death (instantaneous dose)	3,000
ISS (with shield) annual	150
Astronaut career limit <i>effective dose</i>*	470
Mars (3 year, incl. surface) annual	1,000
Large solar flare (free space)	10,000

ICRP cancer risk estimate: 5% per Gy ~ **5% per Sv** (for Q=1)

1 in 20,000 risk of fatal cancer per 1mSv dose (lifetime)

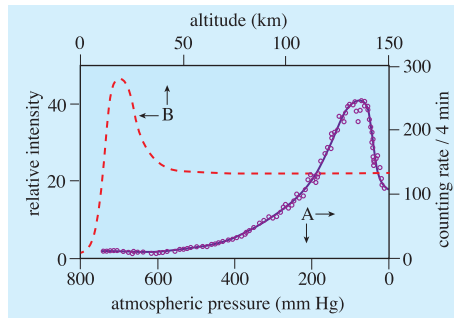
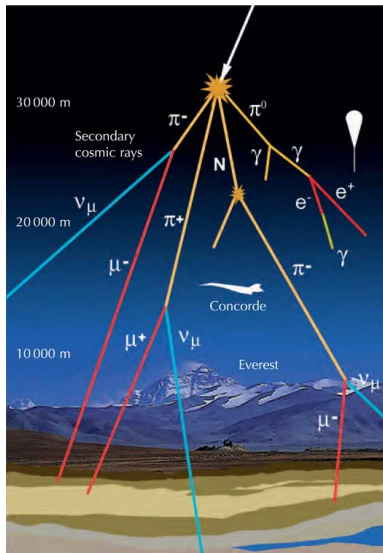
* 30 year old female, 1 year mission (50 yr m/f ~ 1,000 mSv)

AIRCRAFT



<http://www.scienceinschool.org/2010/issue14/cloud/maltese>

AIRCRAFT



Bancroft et al., Phys. Ed. vol.49, p.164, 2014

<http://www.scienceinschool.org/2010/issue14/cloud/maltese>

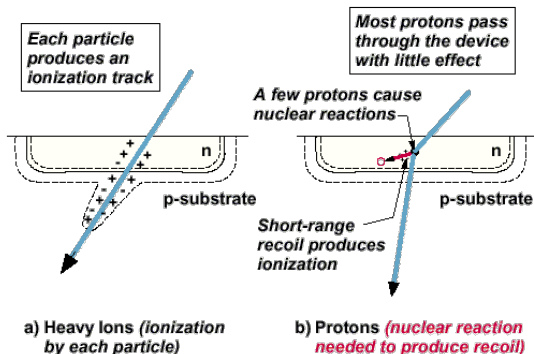
- Domestic crews 1 - 2 mSv /yr
- International crews < 4 mSv / yr
- Pregnant woman < 5 mSv
(to fetus per pregnancy)

AIRCRAFT - WHY ALL THE CONCERN NOW?

- NCRP & ICRP have lowered radiation worker exposure
 - 50 mSv / yr to 20 mSv / yr
- Air crews most highly exposed of any occupation group
- FAA criticized for not paying enough attention
- Many more polar flights
- Future High Speed Civil Transport (HSCT) radiation levels
 - 3 times higher than for crews of subsonic transport
- Only solution available now:
 - reduce flight hours
- **NAIRAS** - Mertens (Langley)

Computers

- Junction density increasing
- Switching energy decreasing



<http://holbert.faculty.asu.edu/eee560/see.html>

Need for predicting Single Event Upsets (SEU)

- satellite electronics
- aircraft electronics (civilian & military)

Shuttle - several hundred SEU / mission

ELECTRONICS - DEEP SPACE

- Electronics on Spirit, Opportunity, Curiosity etc. are radiation hardened
- Shielding very important for Jupiter, Saturn



<http://mars.jpl.nasa.gov/msl/multimedia/images/?imageid=3504>



Credit: NASA/JPL/Space Science Institute

<http://photojournal.jpl.nasa.gov/catalog/PIA04866>

These are the doses received

- How were results obtained?
- How to design spacecraft & aircraft shields so dose is minimal?

Need

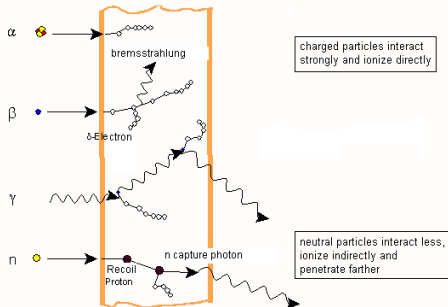
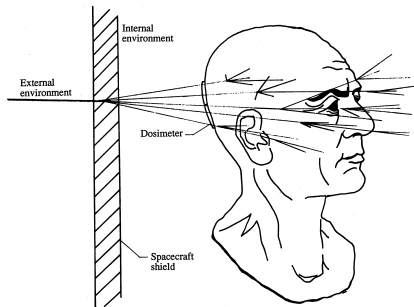
- Accurate atomic, nuclear, particle physics theory
- Accurate transport theory
- Biological models

TRANSPORT

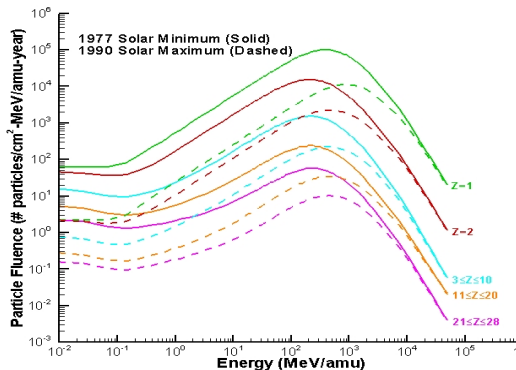
Solve Boltzmann transport eqn (HZETRN)

Deterministic, not Monte Carlo

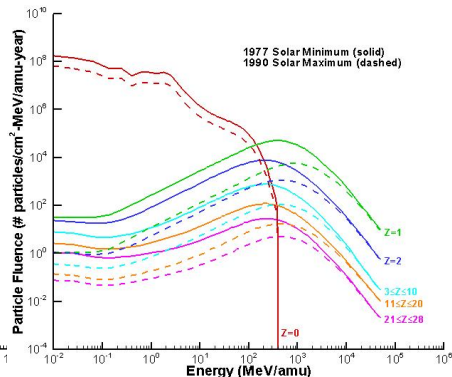
- Want quick answers
- Real time dose as function of position & time
- Both transport & nuclear physics must run fast
- → Applied nuclear physics



TRANSPORT



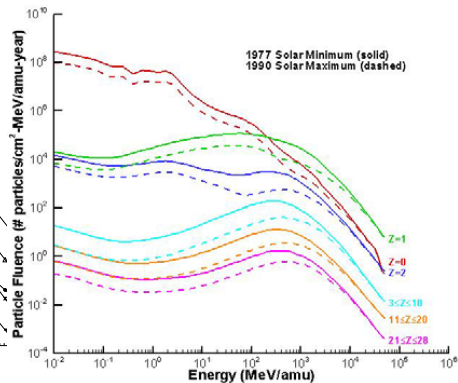
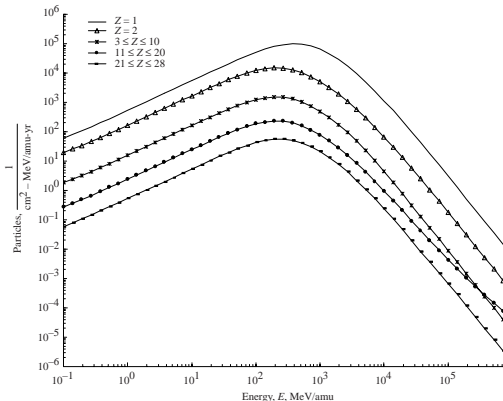
Free space GCR environment at 1AU



Lunar surface environment due to GCR

Cloudsley et al., AIAA, 2006

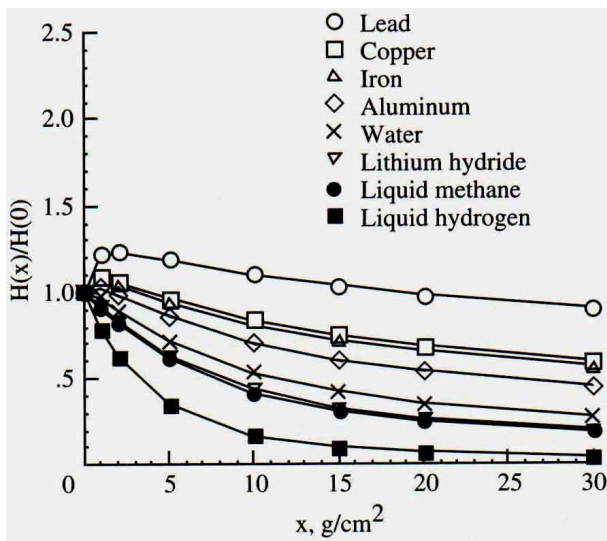
TRANSPORT



Left: Primary GCR spectra at Mars for 1977 solar minimum Kim et al., NASA TP 208724, 1998

Right: Martian surface environment due to GCR Cloudsley et al., AIAA, 2006

TRANSPORT - MATERIALS COMPARED TO ALUMINUM



Dose Equivalent as a function of depth for various materials

Wilson et al., Materials & Design vol.22, p.541, 2001

From radiation point of view, safest place is inside liquid hydrogen fuel tank!

Major result

- Low Z materials required for weight reduction necessary for future High Speed Civil Transport (HSCT) and for future spacecraft are *also* the best radiation protection materials
- Thank goodness!

Short duration

- Solar particle events

Long duration

- Solar particle events
- Galactic cosmic rays

Lunar regolith composition

<u>Material</u>	<u>Mass percentage</u>
-----------------	------------------------

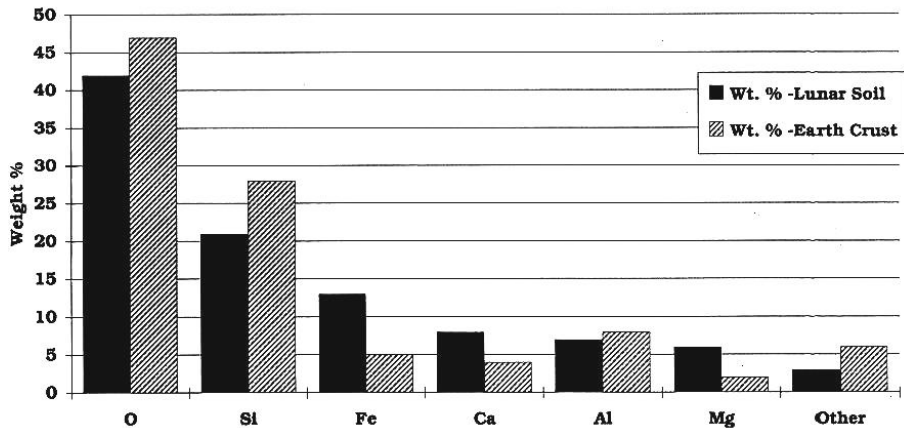
SiO ₂	52.6%
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FeO	19.8 %
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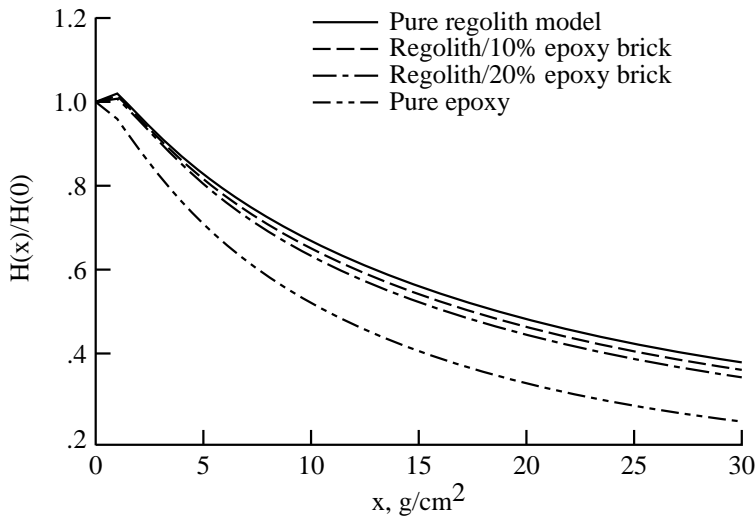
Al ₂ O ₃	17.6 %
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MgO	10.0 %
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The Surface of the Moon is Slightly Richer in Fe, Ca, and Mg Compared to the Earth's Crust



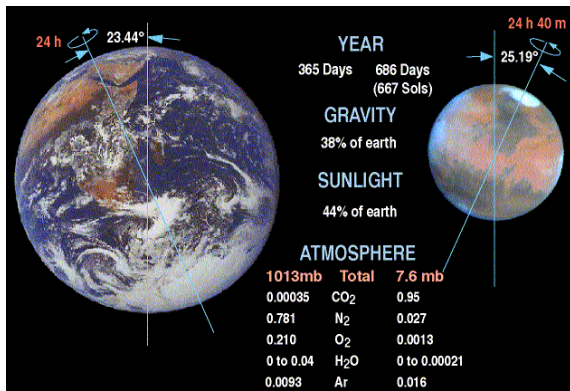
<http://fti.neep.wisc.edu/neep602/lecture12.html>



Attenuation of dose equivalent due to 1977 solar minimum GCR

Simonsen et al., NASA Conference Publication 3360, 1997

	Earth	Mars
Atmospheric thickness (g/cm ²)	1000	20
Magnetic field (Gauss)	1	0



<http://www-k12.atmos.washington.edu/k12/resources/>

Chemical composition of Martian atmosphere

Component	Percentage (%)
CO ₂	95.32
N ₂	02.70
Ar	01.60
O ₂	00.13
CO	00.08

De Angelis et al., Rad. Meas. vol.41, p.1097, 2006

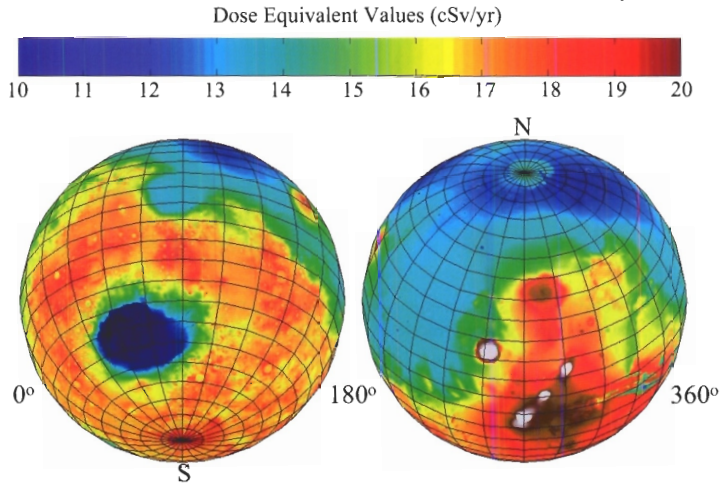
Chemical composition of Martian surface

Component	Percentage (%)
SiO ₂	44.2
Fe ₂ O ₃	16.8
Al ₂ O ₃	08.8
CaO	06.6
MgO	06.2
SO ₃	05.5
Na ₂ O	02.5
TiO ₂	01.0

De Angelis et al., Rad. Meas. vol.41, p.1097, 2006

GCR Environment

20 cSv/year = 200 mSv/year



Model prediction of dose equivalent from GCR. Calculations are shown at average skin depth near solar maximum. Cucinotta, Rad. Res. vol.43, p.S35, 2002

Curiosity MSL RAD Zeitlin et al. Science vol. 340, p.1080, 2013

Mars transit inside vehicle: 1.84 ± 0.33 mSv / day

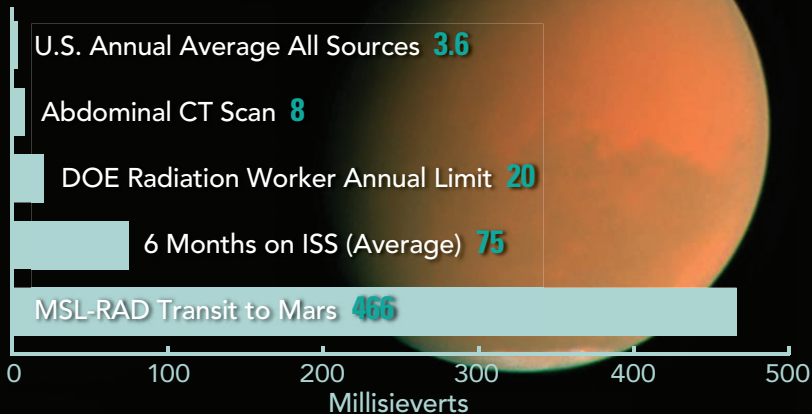
⇒ MSL (one way) 253 days gives 466 mSv

⇒ 331 mSv for 180 day cruise DRM

⇒ 662 mSv return trip

- Plus surface exposure 200 mSv ?
- Approaching and exceeding limits

Comparative Radiation Exposures

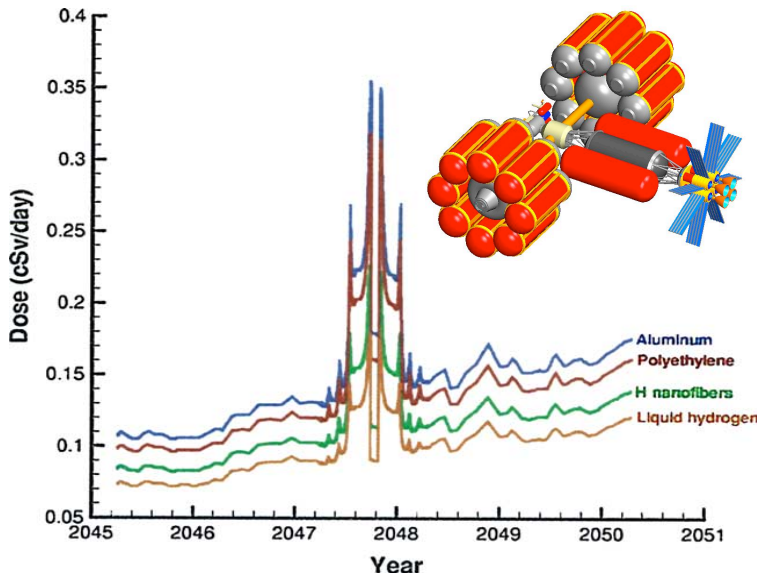


MSL-RAD= Mars Science Laboratory Radiation Assessment Detector [Kerr, Science vol.340, p.1031, 2013](#)

Intense radiation

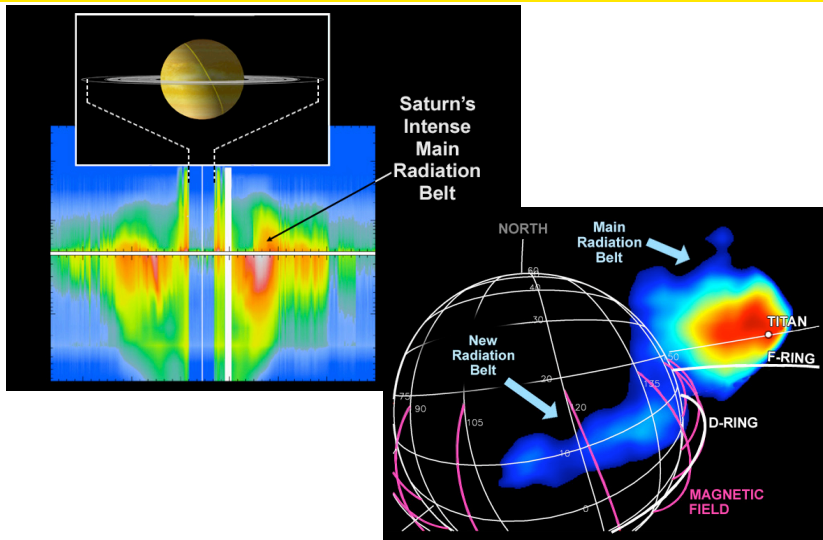
- On Jupiter moon Io humans could not survive for more than a few hours
- Callisto

L1 TO CALLISTO SURFACE OPS (30 DAYS) & RETURN



Wilson et al., Adv. Space Res. vol.34, p.1281, 2004

SATURN



<http://www.universetoday.com/15381/radiation-on-saturn/>

http://www.nasa.gov/mission_pages/cassini/multimedia/pia06421.html

HEALTH EFFECTS ON HUMAN BODY

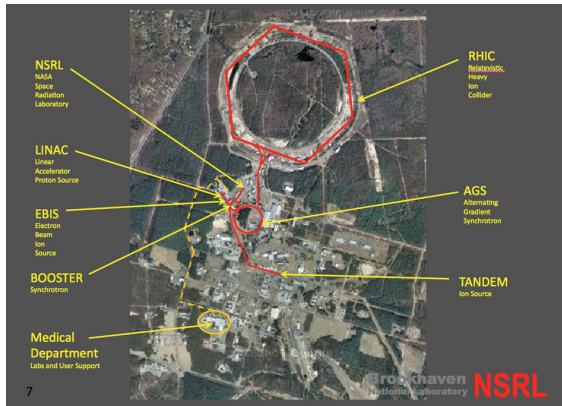
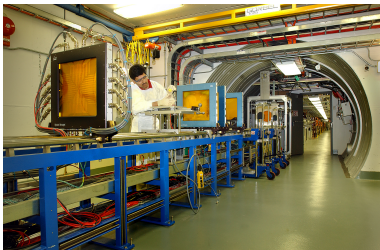
- Carcinogenesis
 - Earlier appearance and more aggressive tumors not seen with controls, gamma-rays or proton induced tumors
 - Persistent oxidative damage and inflammatory pathway responses
 - New genomics data showing distinct gene expression profiles in HZE versus γ -ray or x-ray irradiated cell models
- Acute Radiation Syndrome due to Solar Particle Events
 - Research addresses dose threshold, dose-rate effects with countermeasure evaluation
 - Future work to understand impact of possible high skin dose and microgravity on immune system and blood forming organs

HEALTH EFFECTS ON HUMAN BODY

- Acute or Late Central Nervous System (CNS) Effects
 - Concern for CNS risks originated with the prediction of the light flash phenomenon from single high-Z high-energy nuclei traversals of the retina; this phenomenon was confirmed by the Apollo astronauts
 - Major uncertainty how to extrapolate results from animals to humans
- Degenerative Tissue or other health effects
 - Occupational radiation exposure from the space environment may result in degenerative tissue diseases (non-cancer or non-CNS) such as cardiac, circulatory, or digestive diseases, & cataracts
 - Mechanisms & magnitude of influence of radiation leading to these diseases are not well characterized

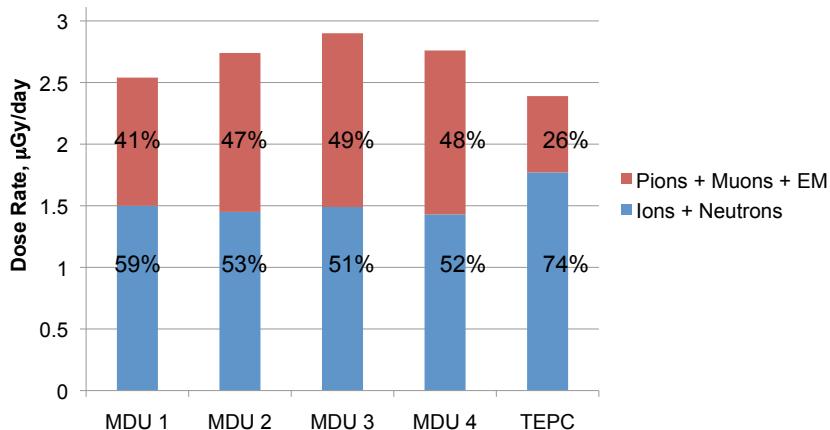
NASA SPACE RADIATION LABORATORY

- Brookhaven National Lab on Long Island
- protons: 4 GeV
- protons - Fe: 50 MeV/n - 1.5 GeV/n
- up to Au: 165 MeV/n



<http://science.energy.gov/np/benefits-of-np/applications-of-nuclear-science/archives/nasa-space-radiation-laboratory-nsrl/>
<http://spaceref.com/missions-and-programs/nasa/nasa-fiso-presentation-an-overview-of-the-nasa-space-radiation-laboratory.html>

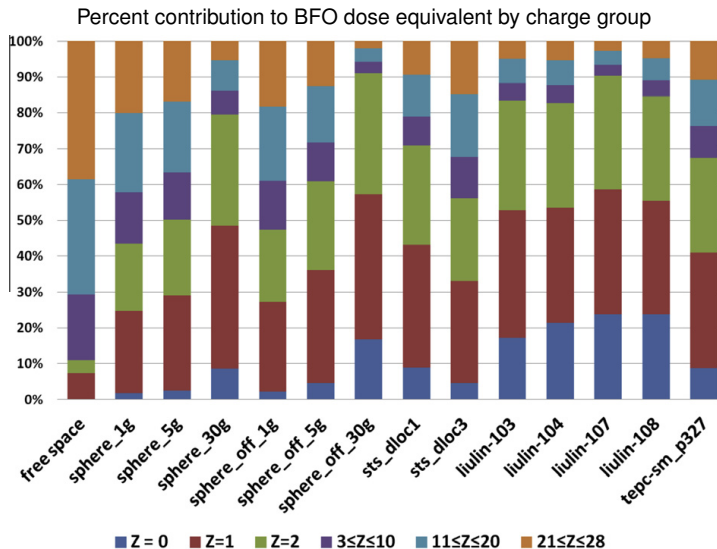
NEW DEVELOPMENTS - PION CONTRIBUTION TO DOSE



Norman, Blattinig, De Angelis, Badavi, Norbury: Adv. Space Res. 50, 146, 2012; Aghara, Blattinig, Norbury, Singleterry: Nucl. Inst. Meth. B 267, 1115, 2009; Slaba et al., NASA TP-2013-217983; Adv. Space Res. 52, 62, 2013;

Pions can contribute almost 50% to dose

NEW DEVELOPMENTS - NEUTRONS & LIGHT IONS



Walker, Townsend, Norbury, Adv. Space Res. vol.51, p.1792, 2013

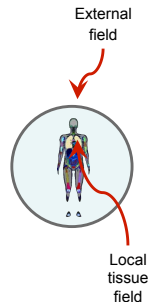
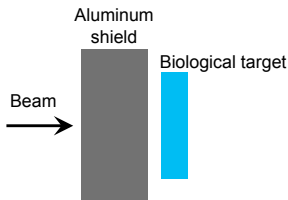
Neutrons and light ions (H, He) can dominate Dose Equivalent

NEW DEVELOPMENTS - GCR SIMULATION

Two approaches to Galactic Cosmic Ray (GCR) simulation:

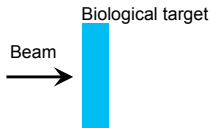
External field approach

Beams selected to represent external, free space field before shielding

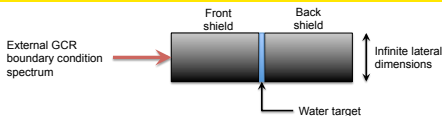


Local tissue field approach

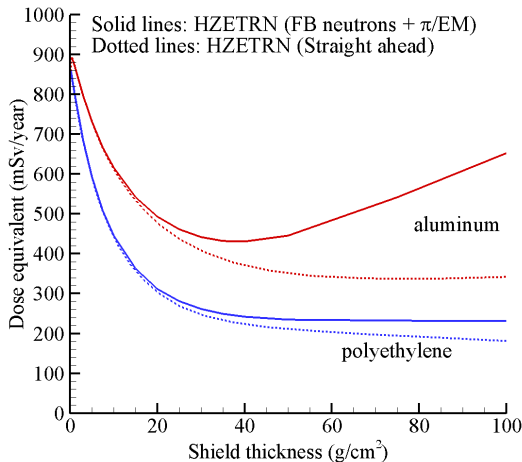
Beams selected to directly represent shielded tissue field



NEW DEVELOPMENTS - MINIMUM DOSE EQUIVALENT VS. DEPTH



$$X \text{ g/cm}^2 \text{ Al} \equiv X \text{ g/cm}^2 \text{ Al front} + 0.03 \text{ mm water} + X \text{ g/cm}^2 \text{ Al back}$$



Blattnig, Slaba, Bahadori, Norman, Cloudsley, Space Radiation Investigators' Workshop, Galveston, TX, 2014

KOREA CONTRIBUTIONS

- Human presence throughout solar system in 21 century
 - International endeavour
 - New frontier - many economic rewards - reaped by participants
- Korea Institute of Radiological and Medical Sciences (KIRAMS)
 - Expertise in proton and heavy ion therapy and radiological sciences
 - Highly relevant to space radiation
- Space Radiation
 - Major uncertainties associated with low dose rate
 - KIRAMS contribution?

CONCLUSIONS

- Human exploration of solar system
- Radiation protection is a major issue
- Fundamental studies in physics and radiobiology still needed
- Republic of Korea could make major contributions

THE END

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